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TITLE: ALIGNMENT AND FOCUSING TOLERANCE INFLUENCES ON OPTICAL PERFORMANCE

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Alignment and focusing tolerance influences on optical performance*

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Abstract

Alignment errors among components of an optical system may substantially degrade the image quality. Focus errors also affect system performance. The potential for serious degradation of image quality is substantial and requires that the tolerances for these errors receive significant attention early in system design. The image quality and reconnaissance performance of an all-reflecting Cassegrain is compared to an all-refractive optical system under conditions of zero and anticipated "real world" misalignments.

Introduction

It has been known since virtually the time of the earliest telescopes that optical devices usually fall significantly short of their analytically predicted possible performance capabilities. The faults layed in the analytical model, which restrict consideration to ideal optical elements without flaw, perfect alignment, and perfectly undisturbed air paths. Of course, everyone knew that these restrictions to ideal parameters were not realistic, but there was computationally no easy way to rigorously handle "real world" imperfect parameters.

It is now possible to model a complete electro-optical system from target to sensor output and even perhaps the sensor interpreter/analyst.[1] While this is now possible, most imaging optical systems continue to be designed with the same basic beginning assumptions of three hundred years ago.

The most seriously underrated of these assumptions is optical alignment, or rather the alignment error, since no optic is perfectly aligned. An analysis of an optical system's performance while its optical components are in a condition of realistic misalignment is essential for scoping what may otherwise be grossly optimistic performance expectations. It is also essential for choosing between alternative optical designs having different sensitivities to alignment errors.

Aligned versus misaligned optical systems

Most optical systems are designed to have their ideal optical and mechanical axes coincident and exhibit rotational symmetry. In the "real world," or non-ideal state, these same optical systems have optical components which exhibit tilt, decenter, and despace errors. Figures 1-4 illustrate a classic all-reflecting Cassegrain in its ideal state and in various states of misalignment, the last being the most realistic, though exaggerated for clarity.

Alignment errors produce image errors.[2] Such image errors, or defects, are also known as aberrations. Axial coma and image displacement are the principal aberrations introduced by tilts and decentrations. Axial coma is similar to third order coma, except it is independent of the distance from the center of the field. Defocus, or focus position error, and spherical aberration are the principal aberrations produced by axial displacement of the image. Misalignment produces chromatic aberrations in refracting lenses. Decentration results in comatic flare and astigmatic separation of the focal plane into two tilted intersecting focal planes. All field aberrations are affected by alignment errors.

Distinct from axial displacement of the image by tilts and decenters is focus error due to the image detector being incorrectly axially positioned with respect to the focal (image) surface. Focus error can result from transient optical component spacing errors not being taken into account. Less well appreciated is the fact that the required focusing precision for an airborne diffraction-limited f/2 lens is beyond the capability and stability of static micropositioners. The appearance and effect of focus error is similar to spherical aberration.

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Analysis: taming the tiger

Fundamentally, one must begin with either 1) the size of alignment error that can be achieved, or 2) the magnitude of the image error (due to alignment error)that can be accepted. If one of these two paramaters is known, the other can be computed. This implies that a determination has been made of the overall image quality required and that an error budget has been or will be made, which divides the permitted image degradation between 1) design deficiencies, 2) component fabrication errors, 3) alignment errors, 4) detector losses, 5) image motion losses, and 6) atmospherics. For the sake of simplicity in the examples to follow, design deficiencies, alignment errors, and detector losses are taken into account, but component fabrication errors, motion losses (vibration and tracking) and atmospherics are ignored.

The optical analyses of the mirror and lens systems were performed utilizing Code V, a versatile and well supported optical design and evaluation computer codes in existence. Code V has a powerful subroutine called TOR which will calculate the constructional errors of an optical system for a given root mean square wavefront error or a given modulation transfer function (MTF) drop at a spatial frequency of interest. Two position errors, tilt and decenter, are among the construction errors computed and quantitatively are equivalent whether the errors occur in the optical substrates themselves or the mounting thereof. The results from TOR's automatic output would be everything needed if it were not for the fact that the performance of a lens needs to be examined in conjunction with its detectors response.

Unfortunately, optical detectors have noise in them, and cannot provide meaningful information at very small modulations. Every detector has a different modulation versus spatial frequency response for a specific input scene contrast ratio. Response curves for detectors are not linear, but may be nearly linear and have a nearly constant MTF for high to moderate input scene contrast ratios. For ease of analysis, a detector threshold of MTF=0.1 was chosen. This is actually a fairly reasonable value for some reconnaissance films when the input scene contrast is about 5:1 to 100:1.

The TOR constructional tolerance output can be used as a general guide in comparing the alignment sensitivities of different lenses. However, any "real-world" comparison requires that each component be misaligned by the realistic amount and then ray traced as if it were a tilted and decentered system. The diffraction MTF resulting is then examined over the MTF values of interest. For this analysis, the resolution "cut off" of the detector at MTF of 0.1 is the figure of merit.

A sufficient number of MTF runs were made to find the "worst case" geometry for the Cassegrain and the triplet. A tilt and decenter of 0.005" among components in a triplet could take place in such a geometry as to be somewhat compensatory. This was not permitted. Iterations were performed until the "worst cast" geometry was established. The performance of the worst casa for each of the Cassegrain and triplet is plotted in Figures 5 and 7.

All-mirror reconnaissance lens

The Cassegrain-type optical system is the most frequently used mirror system. It is compact, simple, and can produce essentially perfect images at the center of the field. To provide nearly diffraction-limited imagery over a field of even 1° requires giving up compactness or adding field lenses or both. The Itek "LOROP" is an example of a compact Cassegrain (19.7" aperture) with good field (1.9°) correction made possible by four field lenses and a spectral filter.[3]

Table 1. Optical characteristics of f/5 Cassegrain

Type	Classical Cassegrain
Focal length	100 inches
Relative aperture	f/5
Field of view	0.5 degrees
Clear aperture	20 inches
Center of pass band	0.65 µm
Resolution (at MTF=0.1)	188 lines/mm
Focal length of prim. mir.	40 inches
Separation between mir.	26.86 inches
Diameter of obscuration	7 inches

The classical Cassegrain, consisting only of two mirrors, a paraboloidal primary and hyperboloidal secondary, was chosen for analysis because of its simplicity. Table 1 details its characteristics. Figure 1 depicts what nearly every designer imagines is true, and Figure 4 depicts what every systems engineer should know is true.

In Figure 5 we see plotted the results of diffraction MTF analyses. The perfect f/5 lens performance cannot be achieved, though close approximations are possible, for example by use of an off-axis (unobscured) Schmidt. The ideal f/5 hybrid Cassegrain performance is approached closely by the Itek "LOROP" system. The "ideal" f/5 Cassegrain is merely the Figure 1 condition, with perfect alignment but all naturally occurring field aberrations present. The next curve to the left indicates that the overall performance of the Cassegrain is only slightly affected by the tilt and decenter errors of 0.005", but the threshold performance is substantially affected, dropping from 188 to 134 cycles/mm (28.7 percent drop in resolution). The left-most performance curve shows the dramatic loss of performance associated with tilt and decenters of 0.010". It is obvious that alignment errors must be held to about 0.005" or less, or serious performance losses will result in this design.

Figure 6 shows the MTF analyses transformed into reconnaissance performance predictions. Note the moderately good agreement between the simple MTF analyses for the perfect 20-inch-diameter lens, the "ideal" classical Cassegrain, and the more complex statistical Itek analysis of the Itek "LOROP" hybrid Cassegrain performance.

Table 2 Alignment affects the standoff range

Clear Aperture	Optical System Deisgnation	Standoff Distance (In nautical miles)
20"	Perfect lens, misaligned 0.000"	60+
19.7"	Itek "LOROP" Hybrid Cass. (Prediction)	50+
20"	"Ideal" Cassegrain, misaligned 0.000"	50
20"	"Real" Cassegrain, misaligned 0.005"	35
20"	"Real" Cassegrain, misaligned 0.010"	5

Table 2 elaborates on Figure 6. It shows that the maximum standoff distance at which a five-foot ground resolved distance (e.g., general identification of missile site, aircraft, command control HQ) can be accomplished is greatly affected by alignment errors. An altitude of 50,000 feet and target ground contrast of 4.7:1 is assumed.

As far as variations on the first order Cassegrain design parameters are concerned, considerable possibilities exist. These variations will definitely have an affect on alignment sensitivity. The analytics describing Cassegrains are well established and understood.[4,5,6] The sensitivity of the secondary mirror to decenter and tilt can be reduced by increasing the primary mirror's focal length or increasing the magnification of the secondary. The sensitivity of the system to mirror spacing error can be reduced by increasing the primary mirror's focal length (increasing the focal ratio).[7] The tilt sensitivity of the primary can be reduced by increasing the primary mirror's focal length or reducing the primary's aperture. In general, primary mirrors faster than f/3 (e.g., f/2 and f/1) should be avoided, as well as secondaries below 2.5X magnification.[8,9] However, this must always be weighed against total system considerations, such as size, volume, weight, rigidity, field of view, photographic speed, image quality, cost, etc.

Mirrors versus lenses

The Cooke triplet used here to represent all refractive lenses was optimized for a wide field, whereas the classical Cassegrain modeled was optimized for a narrow field. Yet, this is a realistic design, since a larger field would be demanded of an all-refracting lens. Table 3 indicates the triplet's optical characteristics.

Table 3 Optical characteristics of f/5 triplet

Type	Cooke triplet
Focal length	20 inches
Relative aperture	f/5
Field of view	4 degrees
Clear aperture	4 inches
Center of pass band	0.65 μm
Resolution (at MTF=0.1)	154 lines/mm

Figure 7 has a surprise in it. The triplet is actually more sensitive to alignment errors than the Cassegrain. Misalignment by only 0.0025 inch, or one half the misalignment of the Cassegrain, produces a drop in threshold resolution efficiency of 36.3 percent. This compares to a 21.8 percent drop for the Cassegrain resulting from tilt and decenter errors of 0.005 inch. At a misalignment of 0.005 inch, the triplet loses 50 percent of its original resolution efficiency to misalignment. Table 4 compares the performance details.

Table 4 A comparison of designs and parameters

Parameter/Type Optic	Misalignment (In inches)	Limiting resolution (In cycles/mm at MTF. = 0.1)	Resolution Efficiency (actual/possible)	Resolution Efficiency Loss Due to Misalignment (In percent)
1) Perfect Optical System (Aberration and obscuration free)	0.000"	248	1.000	00.0
2) "Ideal" Cassegrain (Aberration zero; obscuration)	0.000"	252	1.000	00.0
3) "Design" Cassegrain (Small residual aberrations obsuration)	0.000"	188	0.758	00.0
4) "Real" Cassegrain	0.005"	134	0.540	21.8
5) "Real" Cassegrain	0.010	12	0.048	71.0
6) "Ideal" triplet (optimized for on-axis, 0° field)	0.000	248	1.000	00.0
7) "Ideal" triplet (optimized for 4° field)	0.000"	154	0.621	00.0
8) "Real" Triplet (optimized for 4° field)	0.0025"	64	0.258	36.3
9) "Real" triplet (optimized for 4° field)	0.005"	30	0.121	50.0
10) Focus error ($\lambda/8$)	0.0006"	228	0.919	8.1
11) Focus error ($\lambda/4$)	0.0013"	160	0.654	35.5
12) Focus error ($\lambda/2$)	0.0026"	80	0.323	67.7

Design philosophy

The larger the space available in which to put optics, the looser will be the alignment tolerances on the individual components.[10] The looser the individual tolerances, the better the prospects for good image quality and reduced costs. These truisms are nearly "Laws of Optics" and should be on every opticist's wall. Components close to a pupil of the system require tight alignment tolerances and those further away require less. Components with more optical power are more sensitive to misalignment than those with little optical power. Selection between alternative system designs should be strongly in favor of the one permitting the largest alignment errors. The system should ideally contain simple alignment points, or there must be adequate optical and mechanical aids to make the alignment simple and its theory understandable.

In many cases, a decision on the nature of a design can be made on the basis of the size of focus error permitted. Parameters 10, 11, and 12 in Table 4 and Figure 8 speak to the significance of the focus error for high performance airborne lenses. If a diffraction-limited image is required, or one that is nearly diffraction-limited, the focus error has to be made as small as $\lambda/8$ optical path difference (OPD) in order to have a negligible effect on the image. At f/5, this means positioning the detector with an accuracy of ±.0006 inch over a wide range of environmental conditions. This may be on the ragged edge of being doable with a judicious choice of materials, but only for a small optic. Certainly to think in terms of the same quality of image at f/2, where a focus tolerance of only ±.0001 inch is the rule, is to automatically require closed-loop wavefront or encircled energy sensors to control focusing.

Conclusions

Optical systems which are required to perform near the theoretical resolution limits are sensitive to misalignment and defocusing. The "real-world" performance of an optical system can be predicted only when image quality is computed on the basis of "real-world" misalignments. Acceptable misalignments are tolerances and should be made part of the optical specifications. Choices between alternative optical designs must be made on the basis of "real-world" performance, which may be vastly different from the initial "ideal" (zero misalignment) performance.

Acknowledgements

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References

1. P. J. Peters, "An extension of image quality: computer modeling a complete electro-optical system," Optical Engineering, 21, 38-42 (1982).
2. W. B. Wetherell, "The Calculation of Image Quality," in Applied Optics and Optical Engineering, Vol. VIII (R. Shannon and J. Wyant, eds.), Academic Press, 1980.
3. H. J. Frederickson, "72-inch long range oblique photography (LOROP) camera," Long focal length, high altitude standoff reconnaissance, Proc. Soc. Photo-Opt. Inst. Eng. 242, 14-21 (1980).
4. W. B. Wetherell, and M. P. Rimmer, "General Analysis of Aplanatic Cassegrain, Gregorian, and Schwarzchild Telescopes," Applied Optics 11, 2817-2832 (1972).
5. W. B. Wetherell, "Image Quality Critera for the Large Space Telescope," in Space Optics, pp. 55-103 (Nat. Academy of Sci.) 1974.
6. J. H. Oberheuser, "Optical system engineering approach to Cassegrain telescope selection, design,and tolerancing," Optical systems engineering, Proc. Soc. Photo-Opt. Inst. Eng. 193, 27-33 (1979).
7. R. N. Clark, "Cassegrain Telescopes: Limits of Secondary Movement in Secondary Focusing," Applied Optics 15, 1266-1269 (1976).
8. E. W. Cross, "Limitations to Telescopic Performance," Proc. Riverside Telescope Makers Conference (W. Schramm, ed., Laguna Niguel, CA 92677), pp. 11-25, 1980.
9. E. W. Cross, "Optical Alignment Tolerances for Cassegrainian Telescopes and Their Impact on Image Quality," Proc. Riverside Telescope Makers Conference (W. Schramm, ed,. Laguna Niguel, CA 92677), pp. 83-89, 1982.
10. R. R. Shannon, "A coherent approach to optical engineering," Los Alamos conference on optics, Proc. Soc. Photo-Opt. Inst. Eng., Vol. 288, pp. 596-600 (1981).

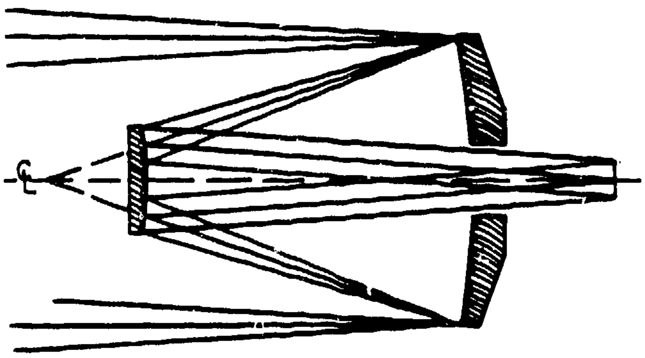

Figure 1. Perfectly aligned Cassegrain telescope.

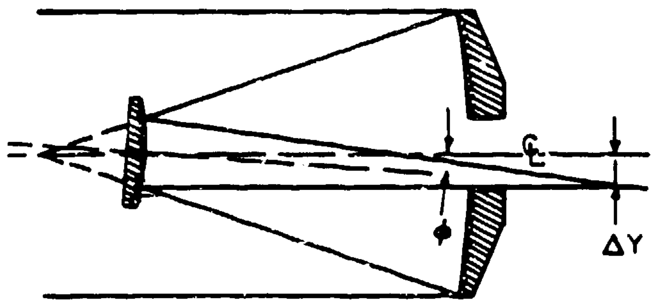

Figure 2 Secondary tilted.

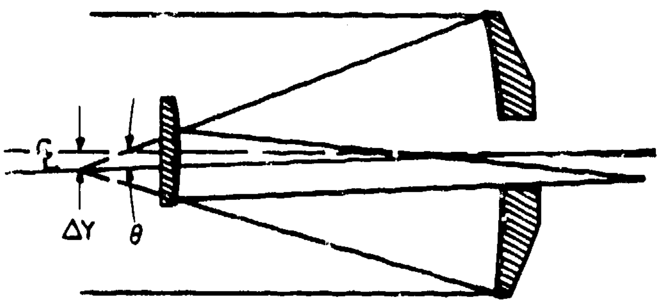

Figure 3. Primarly tilted.

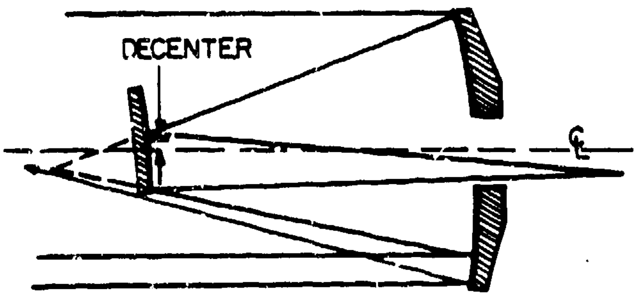

Figure 4. Secondary tilted, Decentered, despaced, and primary tilted. (Exaggerated real conditions.)

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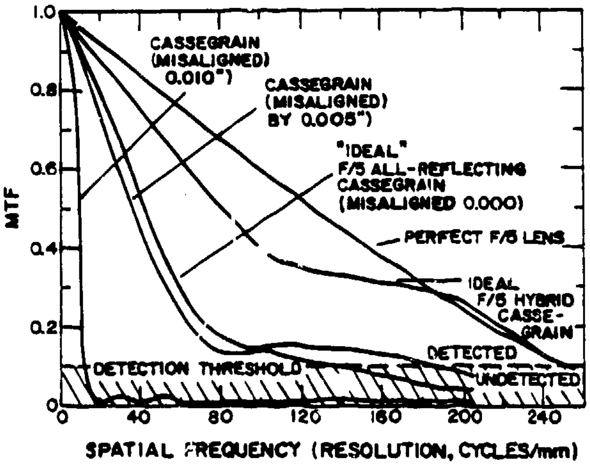

Figure 5. The on-axis performance of the Cassegrain.

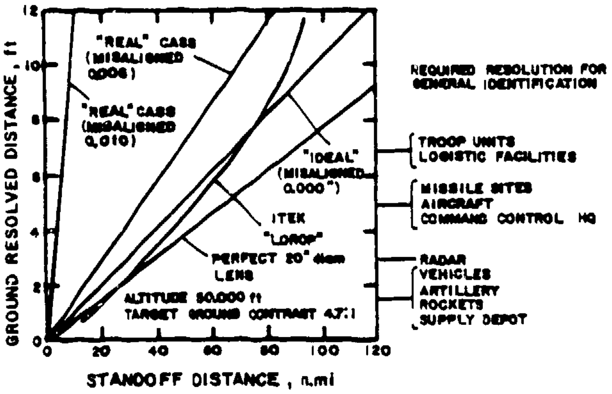

Figure 6. Predicted reconnaissance performance of Cassegrain-type cameras (after Frederickson, 1980).

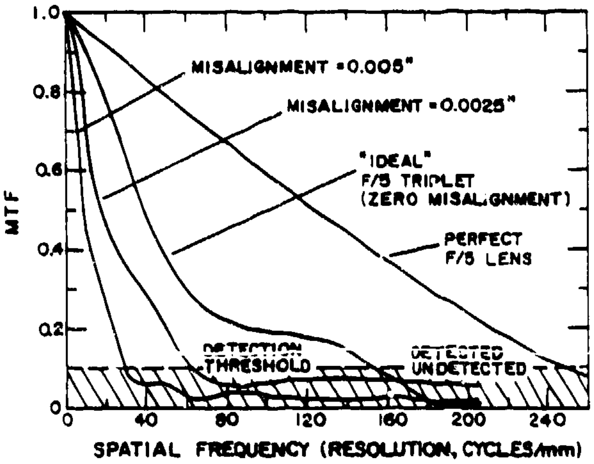

Figure 7. The on-axis performance of the wide-field triplet lens.

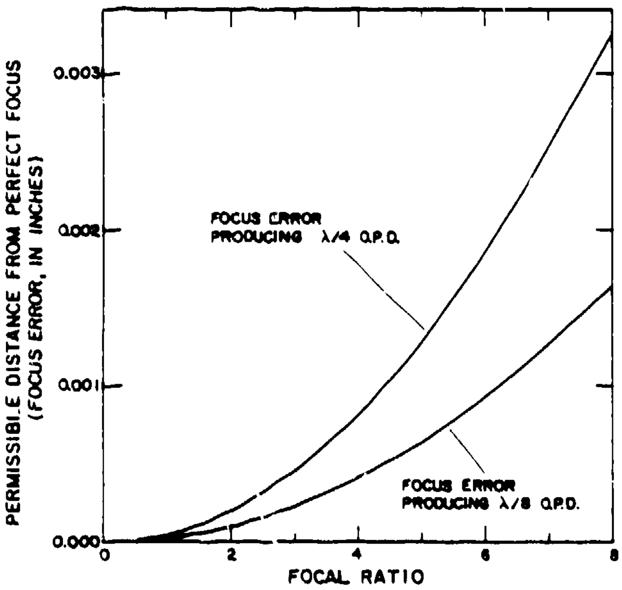

Figure 8. The permissible focus error.